

## On the venus bow shock compressibility

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### Abstract

The effect of the solar wind dynamic pressure on the bow shock of Venus is examined. When the shock crossing distances are normalized to fixed solar wind Mach number, interplanetary magnetic field orientations, and EUV flux value, the scatter of the terminator plane crossings is considerably reduced. The normalized bow shock crossing data show that the size of the bow shock is insensitive to changes in the solar wind dynamic pressure.

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### 1. Introduction

The location of the planetary bow shocks provides information on the nature of the planetary obstacle to the solar wind flow. The bow shock heats the solar wind and deflects it around the planetary obstacle. Other than in the region of backstreaming particles, the bow shock provides the earliest evidence in the solar wind frame of the approaching obstacle to the flow. Because the bow shock location and shape are determined by the size and shape of the effective obstacle, a study of this location can be used to probe the nature of the obstacle even when that obstacle is inaccessible to direct probing, as was the subsolar Venus ionopause during much of the Pioneer Venus Orbiter (PVO) mission.

The terrestrial bow shock position varies greatly in response to changing the solar wind dynamic pressure (Fairfield, 1971). This compressibility is typical of intrinsic field obstacles. If there is an intrinsic global dipole field to stand off the solar wind, then one would expect the bow shock location to exhibit a sixth root dependence upon solar wind dynamic pressure. In the absence of an intrinsic field, the obstacle may be the

ionosphere which is far less compressible. At Venus, for example, the solar wind plasma interacts directly with the ionosphere and upper atmosphere. Although Venus has no detectable intrinsic magnetic field, the solar wind is still deflected about the ionopause with the formation of a detached bow shock because the diffusion time of the magnetized solar wind plasma into the ionosphere, under typical conditions at solar maximum, is very long. By classifying the PVO shock crossings in terms of the solar wind plasma parameters, the effects of solar wind dynamic pressure, Mach numbers, interplanetary magnetic field (IMF) orientation, and solar cycle on the bow shock have been deduced (cf. Slavin et al., 1980; Russell et al., 1988; Zhang et al., 1990). Russell et al. (1988) have shown that the cross-section of the shock has an asymmetry controlled by the direction of the IMF, related to the asymmetry of the velocity of the fast magnetosonic mode that compresses the plasma. The wave speed depends on its direction of propagation relative to the magnetic field. The distance at which the shock stands off from the obstacle also depends on the magnetosonic Mach number, going to infinity as the Mach number approaches unity (Russell et al., 1993; Farris and Russell, 1994).

Many previous researchers have examined the response of the bow shock position to the changes in the

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solar wind dynamic pressure. For example, Tatrallyay et al. (1983) found that the shock terminator radius decreases as the solar wind dynamic pressure increases. Russell et al. (1988) reported that the dependence of the Venus bow shock location on the dynamic pressure is weak and is measurable only at the lowest Mach numbers and high EUV. However, because various solar wind parameters often change concurrently, the controlling parameter may be ambiguous. For example, the Mach number and the solar wind dynamic pressure are highly coupled because they both depend on the solar wind density and velocity. It is difficult to separate the effect of one from the other. Thus the mechanisms through which the solar wind controls the Venus bow shock location are still undetermined.

Khurana and Kivelson (1994) have developed a shock surface model that depends on the Alfvén Mach number, the sonic Mach number, and the direction of the IMF. This model is useful for investigating the variations in the magnetosonic Mach number associated with the multiple change of parameters in the solar wind. Using the model, we can test the dependence of the bow shock location on the solar wind dynamic pressure. In this note, we use the model to normalize the PVO terminator plane bow shock crossing data to a common solar wind condition. We find that changes in the solar wind dynamic pressure do not have any measurable effect on the size of the bow shock.

## 2. Observations

To study the solar wind and IMF control of the Venus bow shock, a database of PVO bow shock crossings near the terminator plane has been created. This data set has been updated and used by various authors (Tatrallyay et al., 1983; Alexander and Russell, 1985; Alexander et al., 1986; Luhmann et al., 1987; Russell et al., 1988; Zhang et al., 1990; Zhang et al., 1991). The database consists of: shock locations in the Venus Solar Orbital (VSO) coordinate system (in VSO coordinates,  $X$  is sunward,  $Y$  opposes planetary motion, and  $Z$  is northward and normal to the orbital plane and completes a right-handed set); upstream magnetic field data; upstream plasma (ion only) parameters; EUV data from the Langmuir probe (courtesy of Brace). In the absence of electron temperature measurements, a fixed electron temperature ( $1.5 \times 10^5$  K) is used to calculate the sound speed.

In this database, the location of the Venus bow shock was determined by examining 12-s resolution magnetic field measurements returned by the PVO magnetometer on orbits nearly perpendicular to the bow shock that crossed it within  $0.5R_V$  of the terminator. Roughly 100 orbits were used each Venus year (224.7 days). The orbital period of the spacecraft is 24 h. It is common to use

the expression PVO season to refer to the time between consecutive returns after the PVO orbit insertion, e.g., PVO season 13 is the thirteenth Venus year since orbit insertion. In this study, we have included measurements of the location of the terminator bow shock from PVO season 1 to season 16.

Using plasma data from the orbiter plasma analyzer (OPA, courtesy of Barnes, Mihalov, and Gazis), velocity and other moments parameters were defined for each orbit, using the relatively constant solar wind measurements on either inbound or outbound legs just outside of the bow shock. Similarly, the IMF vector was defined for each orbit using the magnetometer measurements whenever the field was steady enough to establish a prevailing value just outside of the bow shock crossing.

### 2.1. Terminator bow shock distance

In order to illustrate the results of earlier studies (e.g., Russell et al., 1988), we plot in Fig. 1 the variation in the terminator position of the bow shock as a function of solar wind dynamic pressure. For this plot, individual measurements of bow shock crossings were extrapolated to the terminator plane using a conic section curve with a focus at the center of the plane and an eccentricity of 0.609 derived from the earlier studies. The aberration of the solar wind by the motion of Venus was taken into account in an average sense by rotating  $5^\circ$  about the Venus orbital pole. It is apparent that the location of the terminator bow shock has a weak dependence on the solar wind dynamic pressure. In addition the shock position is highly variable. Part of the variation of the shock position seen in Fig. 1 can be attributed to long-term effects such as EUV flux variations and part to

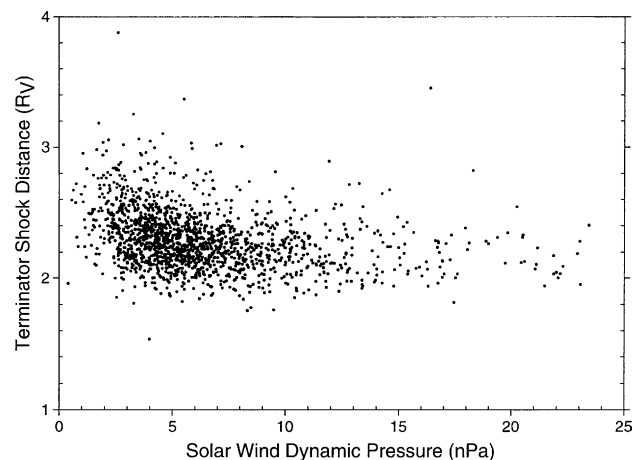


Fig. 1. The dependence of the bow shock position on solar wind dynamic pressure. Solid circles are the individual measurements for each bow shock crossing. The shock locations were extrapolated to the terminator plane using an ellipse centered on the planet with eccentricity 0.609 (Russell et al., 1988). No normalization has been applied to the data.

short-term effects, such as the variation of solar wind Mach number and IMF orientation.

## 2.2. Normalized terminator bow shock distance

Previous studies show that the bow shock position at Venus varies with solar Mach number, intensity of the solar EUV flux and IMF orientation. Thus in order to reveal the effect of the solar wind dynamic pressure alone on Venus bow shock, we have to normalize all the data to a common solar wind and IMF condition simultaneously. In another words, we have to correct for all the other effects which cause the shock position to vary.

The shock response to changing solar conditions can be evaluated using the above-mentioned Khurana and Kivelson (1994) semi-empirical, semi-theoretical model. In this model the Venus bow shock is parameterized by the solar wind conditions. The model begins with a conic section base model taken to be correct for average solar wind conditions. Then modifications will be applied to the base model to account for the changes in the size and shape of the bow shock caused by changes in the prevailing solar wind Alfvén and sonic Mach numbers, and interplanetary magnetic field orientation. Since the model deals with several solar wind parameters simultaneously, it allows us to normalize the bow shock crossing data to common solar wind conditions. For a detailed description of the model, the reader is referred to the original paper by Khurana and Kivelson (1994).

Before we apply the model to our database, we first must correct for the EUV effect. To do so, we plot the aberrated shock terminator distance as a function of EUV flux and apply the best fit. Then, we use the best fitted function to normalize the shock terminator distance to a common EUV flux at  $1.25 \times 10^{12}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ . Fig. 2 shows the terminator shock distance

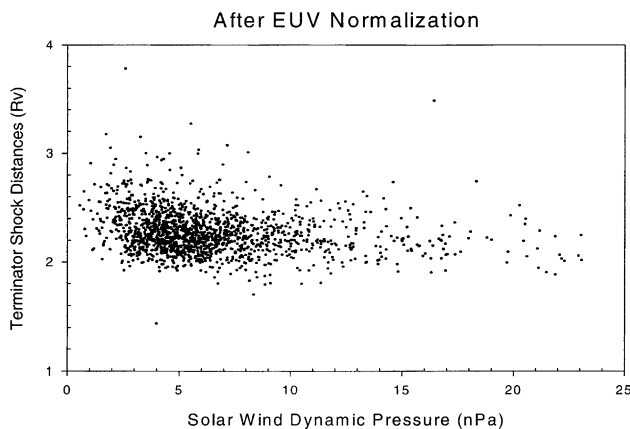


Fig. 2. The dependence of the bow shock position on solar wind dynamic pressure. The PVO bow shock crossing data were extrapolated to the terminator plane and normalized to common EUV flux condition,  $\text{EUV} = 1.25 \times 10^{12}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ .

after the EUV normalization. It is valid to normalize the EUV effect without accounting for changes in the other parameters that affect the shock position, because while these parameters change greatly on short time scales, they are relatively constant over the solar cycle.

After removing the effect of changing EUV flux, the PVO bow shock crossing data were extrapolated to the terminator plane and normalized to average solar wind and IMF conditions ( $M_s/M_a = 1.2$ ;  $\theta_{\text{BN}} = 90^\circ$ ;  $M_a = 6.9$ ) using the model. Fig. 3 shows the normalized bow shock position versus solar wind dynamic pressure. Solid circles are the individual measurements for each bow shock crossing. The straight line is the linear best fit of the data. The straight line intersects on both Y-axis at  $2.399R_v$ . The correlation coefficient is 0.00. As expected when the shock crossing distances are normalized to a common solar wind condition and EUV flux value, the scatter of the terminator plane crossings is reduced. The results shown in Fig. 3 indicate that bow shock position at Venus is independent of the solar wind dynamic pressure. The remaining scatter may be caused in part by time variations of the upstream plasma and associated motions of the bow shock. Another source of scatter in the data is the variation of electron temperature which we took as constant.

To understand our finding that the bow shock is insensitive to the solar wind dynamic pressure, we have to consider the variation of the Venus ionosphere. At solar maximum, the ionosphere is extremely variable and the height of the ionopause is sensitive to the solar wind dynamic pressure. Under usual solar wind condition, the solar wind dynamic pressure effect contributes about

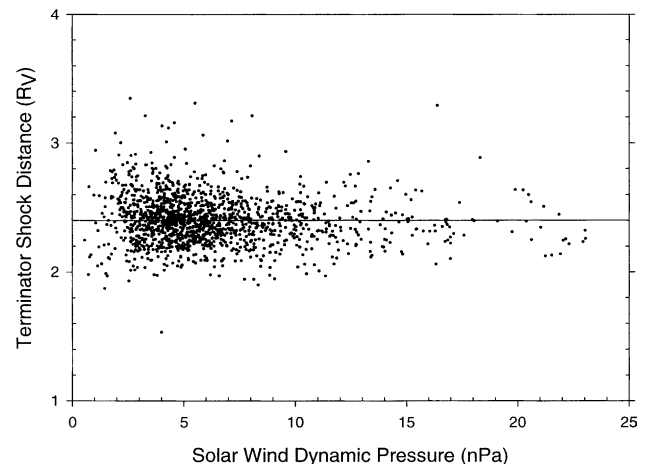


Fig. 3. Normalized bow shock position versus solar wind dynamic pressure. The PVO bow shock crossing data were extrapolated to the terminator plane and normalized to common solar wind and EUV flux conditions, and same  $\theta_{\text{BN}}$  using the model ( $M_s/M_a = 1.2$ ;  $\theta_{\text{BN}} = 90^\circ$ ;  $M_a = 6.9$ ,  $\text{EUV} = 1.25 \times 10^{12}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ ). Solid circles are the individual measurements for each bow shock crossing. The straight line is the linear best fit of the data. The straight line intersects on both Y-axis at  $2.399R_v$ . The correlation coefficient is 0.00.

50 km variation of the ionopause height which is about 300 km in altitude. Although this ionopause variation is significant in the scale of ionopause height, it is negligible when we consider the obstacle size of the bow shock which is about 6300 km at subsolar point. Finally, on extremely rare occasions, the solar wind may almost disappear. At those times the solar wind pressure may drop as low as 0.05 nPa and the ionopause, and also the shock, may expand significantly (Russell et al., 1993). We emphasize that these solar wind pressure conditions are extremely rare.

### 3. Conclusions

In this study, we studied the effect of the solar wind dynamic pressure on the size of the Venus bow shock. Care has been taken to include all effects that could possibly affect the size of the shock. We have normalized the terminator shock distance to a common solar wind condition and IMF orientation. We have also accounted for the EUV effect and the aberration of the solar wind. As we mentioned in the introduction, the Mach number and the solar wind dynamic pressure are highly coupled because they both depend on the solar wind density and velocity. It is difficult to separate the effect of one from the other. Nevertheless, we note that the Mach number is proportion to the square root of the solar wind dynamic pressure. Since the relationship is nonlinear, when we remove the Mach number effect on the bow shock, the solar wind dynamic pressure effect remains.

We have applied the model from Khurana and Kivelson (1994) to account for the effects of plasma parameters and the IMF on the Venus terminator bow shock. We find the scatter of the individual shock crossings is reduced. Unambiguously that the solar wind dynamic pressure has no effect on the size of the bow shock. Thus the obstacle size of Venus is essentially independent of the solar wind dynamic pressure. All the other effects on the shock location are as revealed by

previous studies (cf. Russell et al., 1988). Only on those rare occasions when the solar wind almost disappears does the size of the ionosphere change sufficiently to affect the standoff location of the shock (Russell et al., 1993).

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